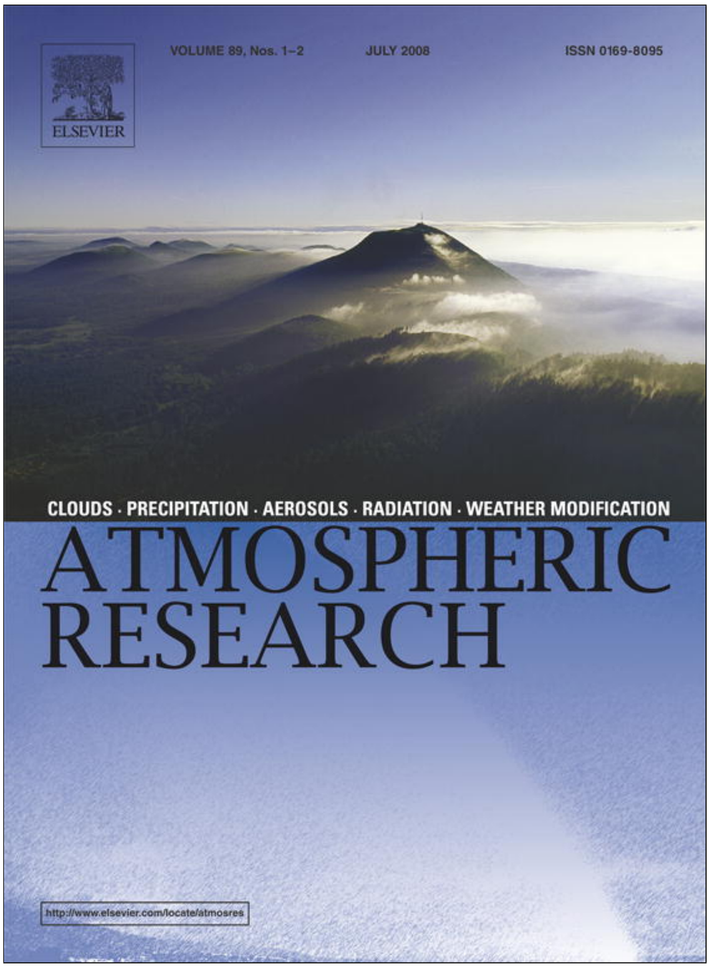
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The contrast and brightness of halos in crystalline clouds

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Abstract

Numerical calculations of the halo brightness and contrast using the discrete ordinate method of the integro-differential radiative transfer equation solution have been carried out for a typical phase function of crystalline clouds exhibiting halo at 22 and 46°. The dependence of halo brightness and contrast on the cloud optical thickness has been investigated. A simple technique to determine the *Ci* cloud optical thickness from the halo contrast measurements is proposed.

Keywords: Halos; Clouds; Discrete ordinate method

It is known that crystalline clouds can exhibit halo phenomena. The position of halos is determined by the hexagonal structure of ice lattice. For a prism angle of 60°, which corresponds to the angle between alternate side faces of a hexagonal ice crystal, the intensity plot shows a sharp maximum at 22°; for the angle of 90°, which corresponds to the angle between a front and a side face, the intensity maximum is smaller and lies at 46°. In halos the rays through each crystal form a collimated beam, and the position of the halo corresponds to the minimum deviation of sunlight from differently oriented crystals. Therefore, random orientation of crystals is needed for the halo formation. This is often the case due to a Brownian rotation.

Another important parameter is the size of crystals. Crystals comparable to the wavelength do not show halo phenomena (Mishchenko and Macke, 1999). Real crystals often have hollows and surface ridges, which reduce the halo visibility. Yet another possibility of the disappearance of halos is the increase of the optical thickness τ of a crystalline cloud. This happens due to multiple scattering effects.

The task of this paper is to examine how quickly halo phenomena disappear with increase of cloud optical thickness. With this in mind, diffuse light transmittance $T=\pi I/\mu_0 F$ for various values of τ has been calculated assuming overhead Sun. Here, I is the intensity of the transmitted light, F is the solar flux density at the top of a cloud, and μ_0 is the cosine of the solar zenith angle. Due to the reciprocity principle, results are valid also for the case of the observation at the zenith direction and the varying solar zenith angle. It is assumed that a cloud can be modeled by a homogeneous plane–parallel layer.

The phase function (Mishchenko et al., 1999) is shown in Fig. 1. It corresponds to randomly oriented hexagonal columns with the ratio length/diameter equal to two and the effective diameter of 100 µm. The asymmetry parameter, which coincides with the average cosine of the scattering angle (Kokhanovsky, 2006), is equal to 0.8117. It was assumed that the crystal projected-area–equivalent-sphere diameters follow the power law distribution with the effective variance of 0.2. Calculations

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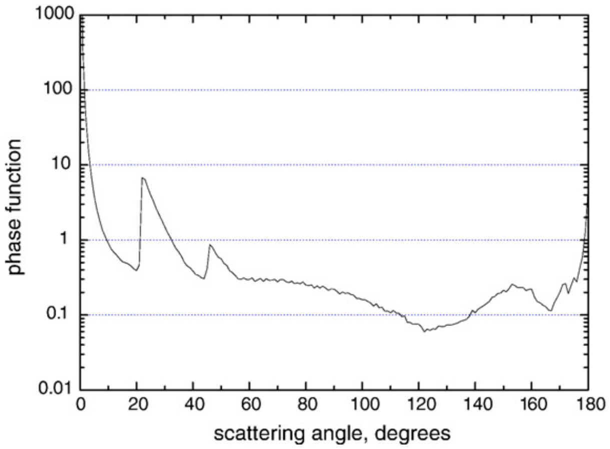

Fig. 1. Phase function.

have been performed using the ray tracing technique coupled with the Kirchhoff approximation (Mishchenko et al., 1999; Mishchenko and Macke, 1998) at the wavelength 0.645 nm, where ice refractive index is equal to $1.3082+0.1382i\times10^{-7}$. One clearly observes both 22 and 46° halos in the single scattering pattern shown in Fig. 1.

Results of radiative transfer calculations of the transmission function using SCIATRAN (www.iup.physik.uni-bremen.de/sciatran) for a nonabsorbing cloud with the phase function shown in Fig. 1 are presented in Fig. 2. The value of T coincides with the intensity of the transmitted light assuming that the solar flux at the top of the layer F is equal to π and $\mu_0=1$. SCIATRAN is the radiative transfer solver based on the method of discrete ordinates (Rozanov and Kokhanovsky, 2006). 2000 coefficients of the phase function expansion in Legendre polynomials as provided by Mishchenko et al. 1999 have been accounted in calculations. The results of calculations at $\tau=0.5$ have been compared against analytical solutions (Kokhanovsky, 2006) of the radiative transfer equation valid at small and large values of τ. Differences are smaller than 1%.

It follows from the analysis of Fig. 2 that basically there are two regimes with respect to the behavior of the brightness of the halo located around 22° observation angle with respect to the cloud optical thickness. The first effect is the brightening of halo with τ. This occurs till cloud optical thickness of 3 (see Fig. 2a) both in the internal dark halo circle and also in the bright ring. For values of $\tau>3$, the increase in the optical thickness leads to the decrease of halo central ring brightness. Halo is very weak at $\tau=10$ and it disappears completely for larger values of τ. Then the angular distribution of the transmitted light is just a linear function of the cosine of the observation angle (Kokhanovsky, 2006) (see Fig. 2b). The brightness of the dark spot inside the halo ring (around 15°, see Fig. 2) increases with optical thickness till $\tau\sim6$ (see also Takano and Liou, 1990) and then it starts to decrease with τ as it should be in the asymptotic regime ($\tau\rightarrow\infty$). Generally, as one can see the intensity of the diffused light is the monotonically increasing function of optical thickness at all angles, if $\tau\leq3$. The dependence $T(\tau)$ at larger τ is more complicated (see Fig. 2b).

The contrast

$$\kappa=\frac{i_{\max}-i_{\min}}{i_{\max}+i_{\min}} \tag{1}$$

is presented in Fig. 3. Here $i_{\min(\max)}$ is the minimal (maximal) value of the transmitted function in the

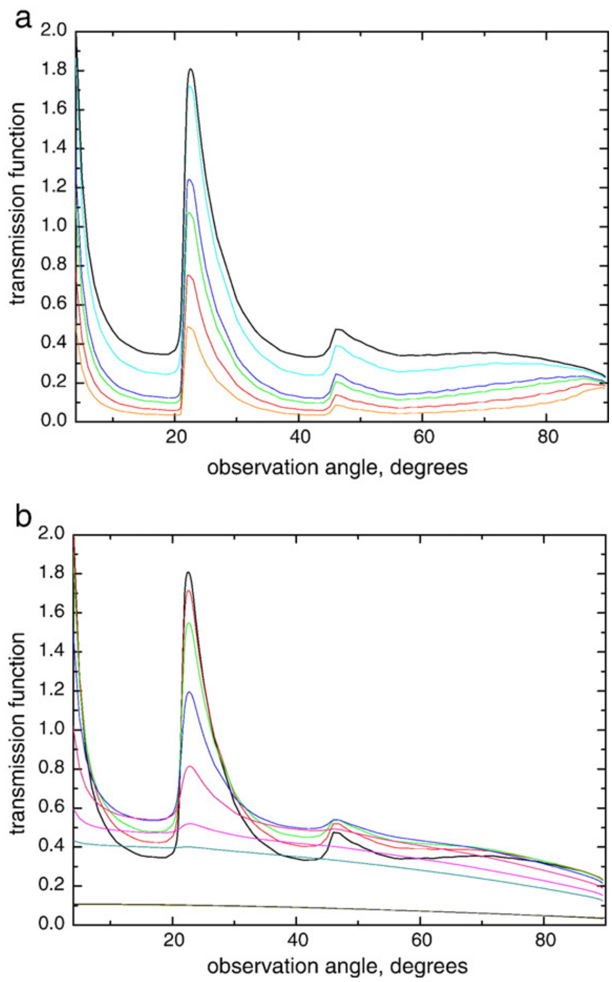

Fig. 2. a. Transmission function for the case of overhead Sun for different values of cloud optical thickness $\tau=0.3$, 0.5, 0.8, 1.0, 2.0, 3.0. Smaller values of τ correspond to lower curves. b. The same as in Fig. 2a except at $\tau=3$, 4, 5, 7, 10, 15, 20, 100. Larger values of τ correspond to lower curves at the observation angle 22°.

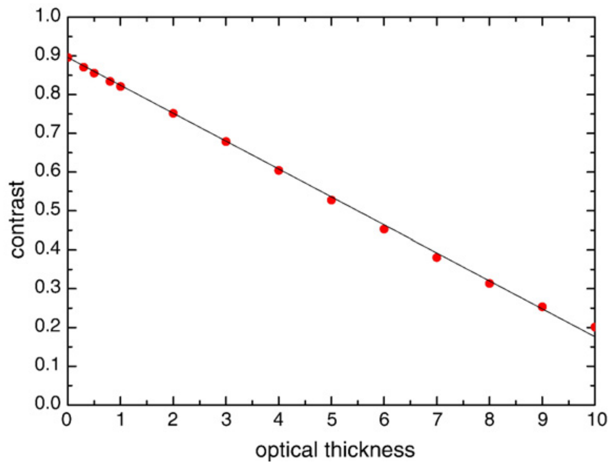

Fig. 3. Dependence of contrast on the cloud optical thickness (circles). The function given by Eq. (2) is presented by a solid line.

angular range 15–30°. It follows that at $\tau \leq 9$, which includes most of *Ci* cloud cases with the visible halo:

$$\kappa = \kappa_0 - \alpha\tau, \tag{2}$$

where $\alpha = 0.072$ and $\kappa_0 = 0.896$ is the contrast for the case of single scattering (see Fig. 1). Eq. (2) suggests a simple way for the determination of cloud optical thickness from the contrast measurement:

$$\tau = \frac{\kappa_0 - \kappa}{\alpha} \tag{3}$$

Summing up, we considered here the modification of halo phenomena due to effects of multiple light scattering. In particular, the enhancement of halo central ring brightness due to multiple light scattering and photon diffusion from the forward narrow peak to the halo region at $\tau < 3$ was studied. A method to determine the cirrus cloud optical thickness from the halo contrast was proposed. Due the reciprocity principle, results shown in Figs. 2 and 3 are also valid for the sky observation at zenith and varying solar zenith angle.

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